401 530

NOLTR 63-52

INTERNAL THERMAL LIMITS OF RUBY LASER PERFORMANCE

11 MARCH 1963

NOL

UNITED STATES NAVAL ORDNANCE LABORATORY, WHITE OAK, MARYLAND

NOLTR 63-52

RELEASED TO ASTIA
BY THE NAVAL ORDNANCE LABORATORY
☐ Without restrictions
☐ For Release to Military and Government Agencies Only.
☑ Approval by BuWeps required for release to contractors.
☐ Approval by BuWeps required for all subsequent release.

NO OTS

INTERNAL THERMAL LIMITS OF RUBY LASER PERFORMANCE

Prepared by:

Irving I. Sochard

ABSTRACT: The operation of a ruby laser is highly dependent on the amount of heat it receives from a light pump. The lower the operating temperature of the ruby the higher the efficiency of the device. This report gives a brief quantitative analysis of the heat transfer rates seen by the ruby and the maximum repetition rates at which the ruby can lase.

U. S. NAVAL ORDNANCE LABORATORY
WHITE OAK, MARYLAND

This report is intended as a brief investigation of the thermal limits of ruby lasers, since these limits are of extreme importance in any future laser investigations. This work was performed under Task #PR-8.

R. E. ODENING
Captain, USN
Commander

R. E. Grantham

R. E. GRANTHAM
By direction

ILLUSTRATIONS

INTERNAL THERMAL LIMITS OF RUBY LASER PERFORMANCE

1. The time averaged coherent light output of a ruby laser at a fixed temperature is proportional to the time averaged input of pump light. The requirement that for steady state operation the heat content of the absorbed radiation must be removed at the rate it is generated is an important limitation on the obtainable power output. This analysis indicates the importance of maintaining low temperatures and high heat transfer rates at the surface of the crystal. This can be practically done by immersing the ruby in a flowing cryogenic liquid. It might be mounted in a transparent double walled evacuated tubing as shown in Figure 1. The most convenient cryogenic liquid is probably nitrogen because of its relatively low cost and high heat of vaporization.

2. The thermal conductivity (K) of ruby at low temperatures is extremely high but drops rapidly at temperatures above 77^{o}K as shown in Figure 2. The radial temperature gradient in a heat generating long cylinder is related to the generated heat per volume, q, by

$$\Delta T = \frac{r^2}{4\bar{K}} \dot{q} \qquad (1)$$

where r is the radius and $\bar{K}$ the average thermal conductivity for the range ΔT. The approximation is made that heat is generated uniformly throughout the crystal. Then

$$\dot{q} = \frac{\dot{Q}_L}{V_L} = \frac{\dot{Q}_L}{\pi r^2} \qquad (2)$$

where Q_L is the heat generated per unit length and V_L is the volume per unit length. Substituting we get

$$\Delta T = \frac{r^2}{4\bar{K}} \frac{\dot{Q}_L}{\pi r^2} = \frac{\dot{Q}_L}{4\pi\bar{K}} \qquad (3)$$

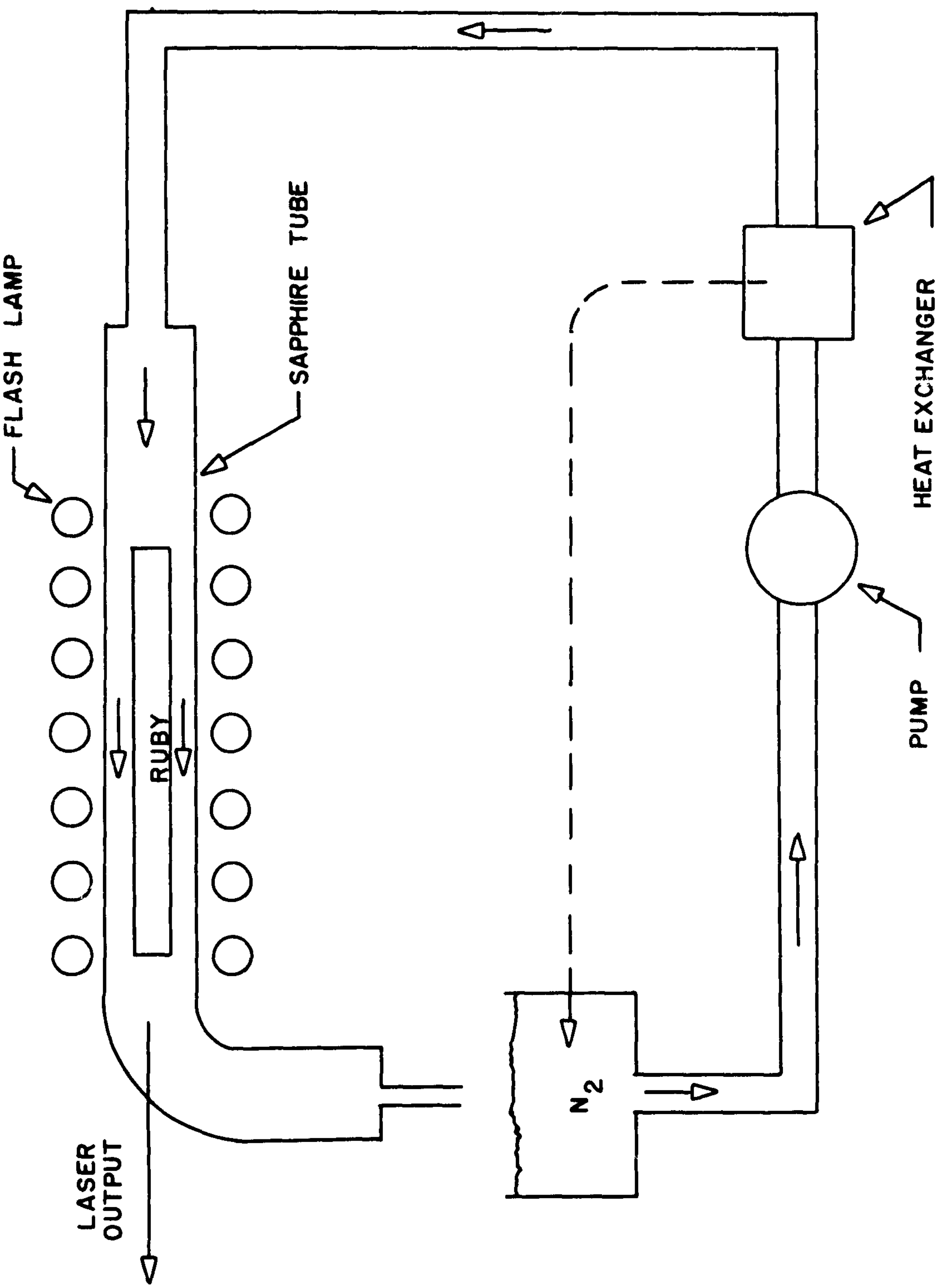

FIG. 1 COOLING SYSTEM FOR RUBY LASER

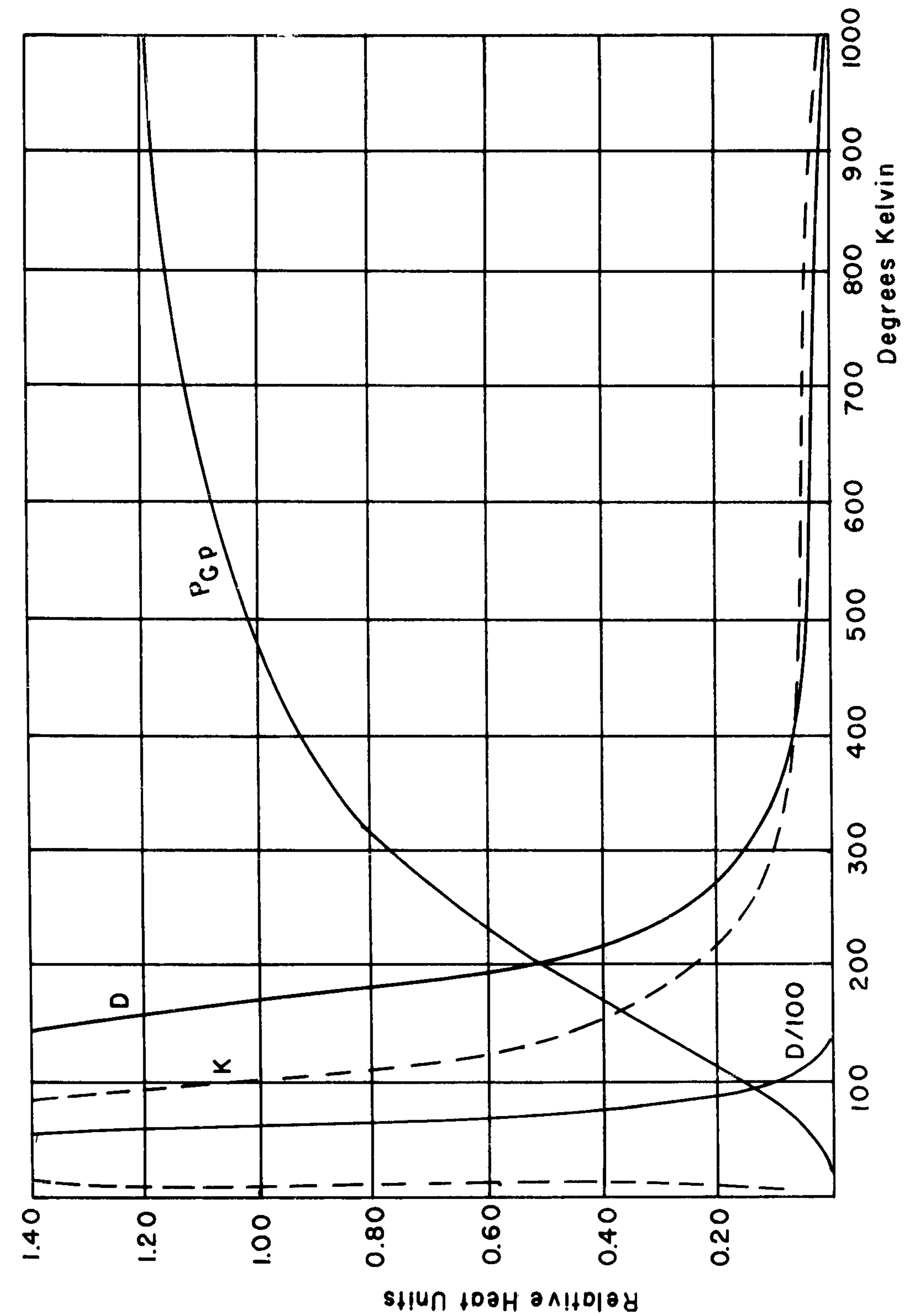

Fig. 2 Thermal Properties of Ruby

$$\dot{Q}_{L} = 4\pi \, \Delta T \bar{K}. \tag{4}$$

This indicates that the time averaged rate of heat removal per ΔT is a function only of length and independent of radius. Figure 3 is calculated from Equation (4) where T_o is the temperature maintained at the surface of the crystal. $\bar{K}$ is approximated by using the value of K at $(T_o + \frac{1}{2}\Delta T)$. Figure 3 indicates that, due to the sharp decrease in thermal conductivity with increasing temperature, $\dot{Q}_L$ can have a maximum as a function of ΔT for a fixed T_o. Since the coherent output per unit length is proportional to $\dot{Q}_L$, it will have a maximum as a function of pumping rate. Based on present technology this will be on the order of 1.0% of $\dot{Q}_L$. The efficiency of conversion of pump light to coherent output falls rapidly with average temperature so the peak output will occur at a substantially lower ΔT than indicated by Figure 3. The values of T_o in Figure 3 represent; 77^oK - maintaining the surface at liquid nitrogen temperature, 100^oK - allowing for a reasonable rise in temperature from the liquid nitrogen to the crystal surface, 300^oK - cooling with a room temperature liquid like water.

3. The maximum pump energy per unit length that can be supplied per pulse, Q_p, can be assumed to be the average heat content above T_o that is present at one time and is approximated by

$$Q_p = \tfrac{1}{2} \, \Delta T(\pi r^2)\rho \, \bar{C}_p \tag{5}$$

where ρ is the density of the crystal and $\bar{C}_p$ is the average value of the specific heat, approximated by the value of C_p at $(T_o + \frac{1}{2}\Delta T)$ in Figure 2. Figure 4 shows the approximate stored energy per unit volume for $T_o = 77^oK$. Since C_p is small at 77^oK, substantial temperature rises will result if large amounts of pump energy are supplied per pulse. As the conversion efficiency drops rapidly with increasing average temperature, there will be a maximum value of coherent output possible. The general relationship between efficiency and average temperature is not know at the present.

4. An approximation of the maximum possible pulse repetition rate can be calculated by defining a response time (τ) as the time required to remove Q_p at a rate of heat removal $\dot{Q}_L$.

$$\tau = \frac{Q_p}{\dot{Q}_L} = \frac{\frac{1}{2}\Delta T(\pi r^2) \, \rho\bar{C}_p}{4\pi \, \Delta T \, \bar{K}} = \frac{r^2}{8} \, \frac{\rho\bar{C}_p}{\bar{K}} \tag{6}$$

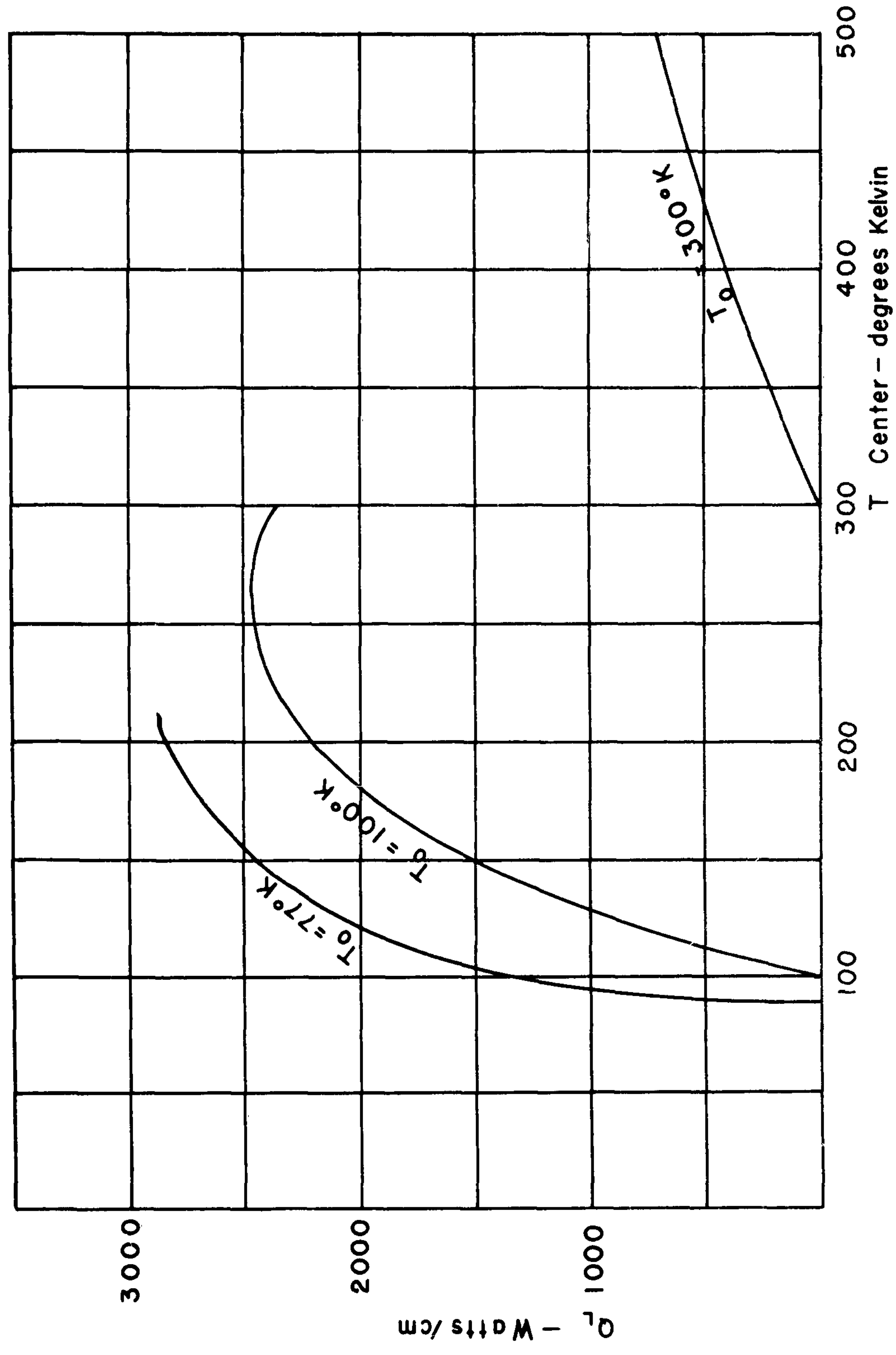

Fig. 3 Heat Generated as Function of Temperature

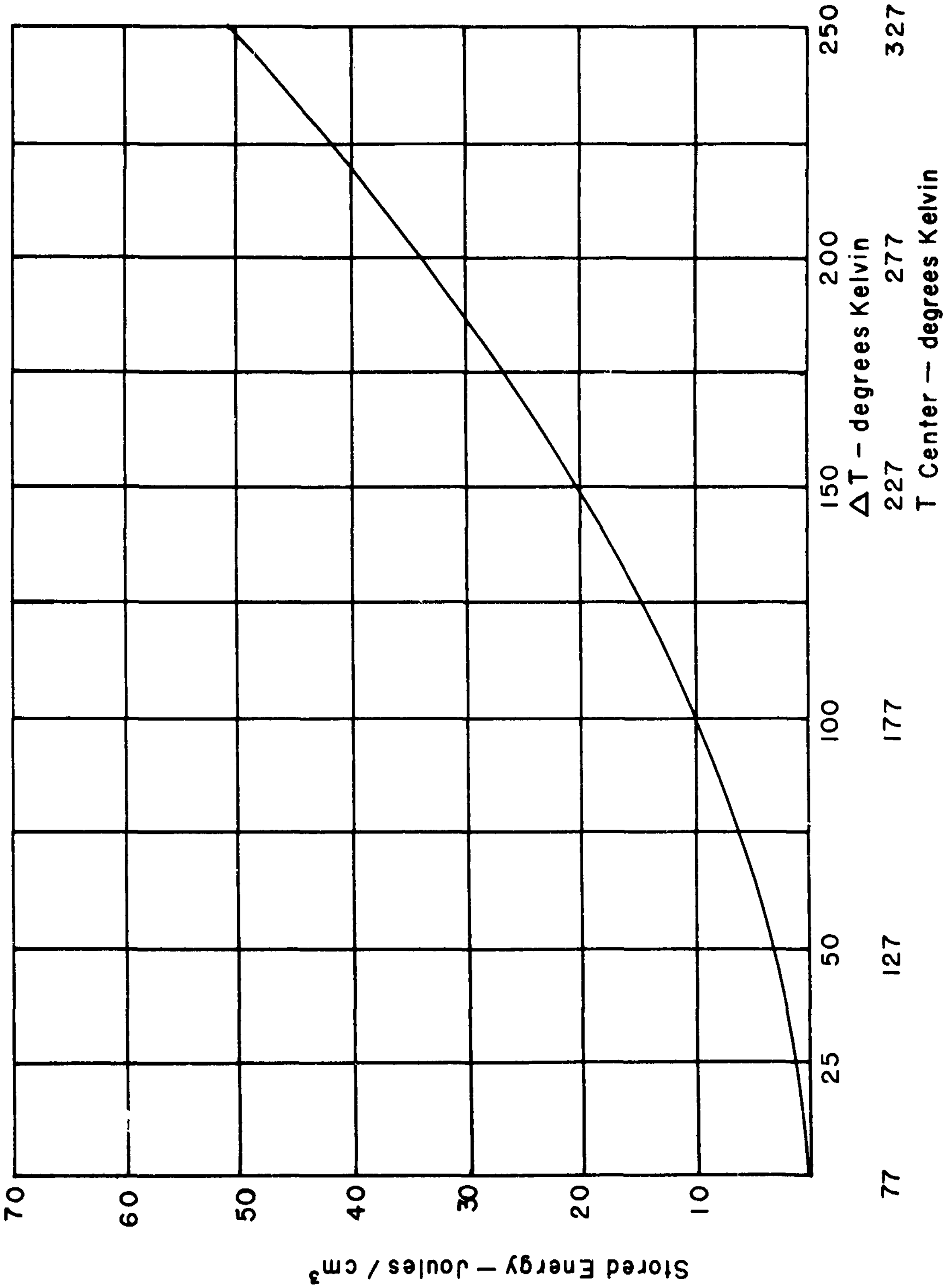

Fig. 4 PumpEnergy Storage in Ruby

$$\tau = \frac{r^2}{8} \frac{1}{\overline{D}} . \qquad (7)$$

The usual definition of the thermal diffusivity, D, has been substituted, see Figure 2. The maximum repetition rate can then be defined as

$$\frac{1}{\tau} = \frac{8\overline{D}}{r^2} \qquad (8)$$

Figure 5 is a plot of Equation (8) as a function of the average crystal temperature.

5. The values given in Figure 3 and 5 represent maximum rates limited only by the thermal properties of the ruby. Below $T_o = 150^oK$ these are probably not obtainable in practice as the system is limited by the possible rate of heat transfer at the crystal-liquid interface. The area rate of heat transfer is limited, at low flow velocities, by the formation of a vapor film and, at high flow velocities, by frictional heating. The exact determination of the maximum possible heattransfer rate for a given liquid would constitute a difficult but feasible project. The average value approximations used in this study are fairly crude and are meant only to be indicative of the general trends. The exact solution can be obtained by a straightforward machine computation. The exact rate of heat generation as a function of position should then be included. This can be calculated from optical absorption coefficient of the pump light.

6. As more information about conversion efficiency as a function of temperature, materials and configuration becomes available the exact solution of the thermal conduction and heat transfer problem should be warranted.

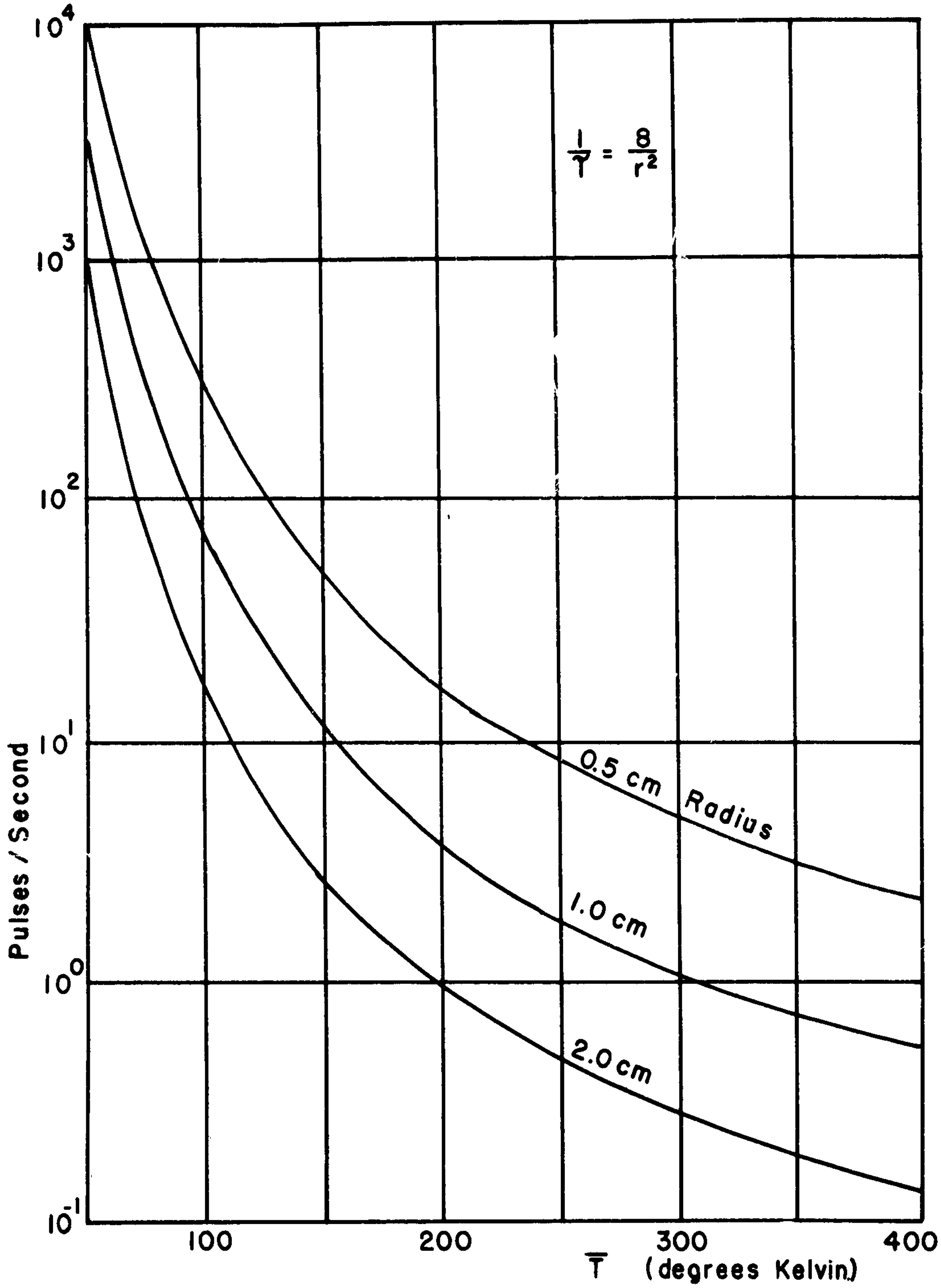

Fig.5 Repitition Rate vs Average Crystal Temperature

DISTRIBUTION

	Copies
Special Projects Office (Dr. Craven, SP-001)	1
Diamond Ordnance Fuze Laboratories Washington, D. C.	1
Naval Ordnance Laboratory Corona, California	1
Naval Ordnance Test Station China Lake, California	1
NADC, Johnsville, Pa.	1
Bureau of Naval Weapons Washington, D. C.	1
RMGA-81 (Mr. Lee)	1
RM-12 (Dr. Tanzos)	1
RMMO	1
RREN	1
Chief, Bureau of Naval Weapons Attn: Library, DIS3 Washington 25, D. C.	4
Armed Services Technical Information Agency Arlington Hall Arlington, Virginia	10
Office of Naval Research Washington 25, D. C. Attn: Laser Group	2

CATALOGING INFORMATION FOR LIBRARY USE

BIBLIOGRAPHIC INFORMATION

	DESCRIPTORS	CODES		DESCRIPTORS	CODES
SOURCE	NOL technical report	NOLTR	SECURITY CLASSIFICATION AND CODE COUNT	Unclassified-32	UØ32
REPORT NUMBER	63-52	63Ø52	CIRCULATION LIMITATION		
REPORT DATE	11 March 1963	Ø363	CIRCULATION LIMITATION OR BIBLIOGRAPHIC		
			BIBLIOGRAPHIC (SUPPL., VOL., ETC.)		

SUBJECT ANALYSIS OF REPORT

DESCRIPTORS	CODES	DESCRIPTORS	CODES	DESCRIPTORS	CODES
Thermal	THER	Input	INPU	Amplification	AMPF
Limits	LIMT	Pump	PUMP	Maser	MASE
Ruby	RUBY	Power	POWR	Optical	OPTI
Lasers	LASE	Low temperature	LOWM	Energy	ENER
Internal	INTO	Surface	SURA	Storage	STOR
Heat	HEAT	Crystal	CRYS	Maximum	MAXM
Temperature	TEMP	Cryogenic	CRYO	Repetition	RPET
Heat transfer	HEAF	Liquid	LIQU	Cooling	COOL
Rates	RATE	Nitrogen	NITG		
Light	LIGT	Conductivity	COND		
Output	OUTP	Immersion	IMMR		
Proportional	PRTI	Ruby (Properties)	RUBYP		

Naval Ordnance Laboratory, White Oak, Md.
(NOL technical report 63-52)
INTERNAL THERMAL LIMITS OF RUBY LASER PERFORMANCE (U), by Irving I. Soohard. 11 March 1963. 8p. diagr., tables. Task PR-8.
UNCLASSIFIED

The operation of a ruby laser is highly dependent on the amount of heat it receives from a light pump. The lower the operating temperature of the ruby the higher the efficiency of the device. This report gives a brief quantitative analysis of the heat transfer rates seen by the ruby and the maximum repetition rates at which the ruby can lase.

Abstract card is unclassified.

1. Lasers, Ruby
2. Lasers - Temperatures
I. Title
II. Soohard, Irving I.
III. Project

Naval Ordnance Laboratory, White Oak, Md.
(NOL technical report 63-52)
INTERNAL THERMAL LIMITS OF RUBY LASER PERFORMANCE (U), by Irving I. Soohard. 11 March 1963. 8p. diagr., tables. Task PR-8.
UNCLASSIFIED

The operation of a ruby laser is highly dependent on the amount of heat it receives from a light pump. The lower the operating temperature of the ruby the higher the efficiency of the device. This report gives a brief quantitative analysis of the heat transfer rates seen by the ruby and the maximum repetition rates at which the ruby can lase.

Abstract card is unclassified.

1. Lasers, Ruby
2. Lasers - Temperatures
I. Title
II. Soohard, Irving I.
III. Project

Naval Ordnance Laboratory, White Oak, Md.
(NOL technical report 63-52)
INTERNAL THERMAL LIMITS OF RUBY LASER PERFORMANCE (U), by Irving I. Soohard. 11 March 1963. 8p. diagr., tables. Task PR-8.
UNCLASSIFIED

The operation of a ruby laser is highly dependent on the amount of heat it receives from a light pump. The lower the operating temperature of the ruby the higher the efficiency of the device. This report gives a brief quantitative analysis of the heat transfer rates seen by the ruby and the maximum repetition rates at which the ruby can lase.

Abstract card is unclassified.

1. Lasers, Ruby
2. Lasers - Temperatures
I. Title
II. Soohard, Irving I.
III. Project

Naval Ordnance Laboratory, White Oak, Md.
(NOL technical report 63-52)
INTERNAL THERMAL LIMITS OF RUBY LASER PERFORMANCE (U), by Irving I. Soohard. 11 March 1963. 8p. diagr., tables. Task PR-8.
UNCLASSIFIED

The operation of a ruby laser is highly dependent on the amount of heat it receives from a light pump. The lower the operating temperature of the ruby the higher the efficiency of the device. This report gives a brief quantitative analysis of the heat transfer rates seen by the ruby and the maximum repetition rates at which the ruby can lase.

Abstract card is unclassified.

1. Lasers, Ruby
2. Lasers - Temperatures
I. Title
II. Soohard, Irving I.
III. Project